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1.0. Introduction

The Optoelectronic Technology Consortium has been established to position U.S. industry as the world leader in optical interconnect technology by developing, fabricating, integrating and demonstrating the producibility of optoelectronic components for high-density/high-data-rate processors and accelerating the insertion of this technology into military and commercial applications. This objective will be accomplished by a program focused in three areas.

1. Demonstrated performance: OETC will demonstrate an aggregate data transfer rate of 16 Gbit/s between single transmitter and receiver packages, as well as the expandability of this technology by combining four links in parallel to achieve a 64 Gbit/s link.

2. Accelerated development: By collaborating during the precompetitive technology development stage, OETC will advance the development of optical components and produce links for a multiboard processor testbed demonstration.

3. Producibility: OETC's technology will achieve this performance by using components that are affordable, and reliable, with a line BER$<10^{-15}$ and MTTF$>10^{6}$ hours.

Under the OETC program Honeywell will develop packaged AlGaAs arrays of waveguide modulators and polymer based, high density, parallel optical backplane technology compatible with low-cost manufacturability.

The packaged AlGaAs modulator arrays will consist of a single fiber input, a 1×4 fanout circuit, four waveguide modulators, and four fiber outputs, all mounted on a ceramic header. The primary benefits to this approach are enhanced system reliability, particularly at high temperatures, and a device design that is highly producible due to the inherent process tolerance. Combined with the demonstrated high density of these devices when fabricated in arrays, this allows the development of compact and reliable transmitter components.

The objective of the polyimide backplane development effort is to demonstrate a practical high density (>20 lines or channels per mm) parallel optical backplane facilitating (bandwidth × length/power) interconnect figures of merit between one and two orders of magnitude greater than would be attainable with state-of-the-art electrical interconnects. The effort will address both development of an ultimately manufacturable and environmentally tolerant optical backplane, and the optical interface concepts required for practical board-to-backplane optical connection. The key functionalities, and compatibility with standard multiboard assembly practices will be demonstrated in a laboratory evaluation system.

Technical progress achieved during the current reporting period, and plans for the next reporting period, are summarized in the following sections.

2.0. Progress Summary

2.1. AlGaAs Modulator Array Development. Task leader: Dr. Charles Sullivan

Activities during the second quarter centered on completing the first pass of a process run using the mask set described in the last quarterly report, and on refining the reactive ion etch and epitaxial growth processes. The activities and results are summarized in the following:

The first-pass fabrication run of three quadrants from 3-inch wafers containing both passive and active components was completed successfully and selected devices from these samples were tested and evaluated. The objective of this experiment has been to identify all critical issues associated with

building waveguide modulator arrays and to establish the optimum array design for good performance and easy producibility. Measurements of propagation loss as a function of waveguide curvature in the splitters in our first-pass experiment suggest that a 1-mm radius of curvature (ROC) may be optimum for our etch process. The results achieved with active devices are illustrated in Figure 1 which shows the measured L-V terminal characteristic of one output from a 1×4 waveguide modulator array when the two arms of a Mach-Zehnder interferometer are reverse-biased independently. VL (voltage-length product for π phase change) and ER (extinction or on-off ratio) for this 1 cm long device are measured to range from 5.3 to 5.6 V-cm and 8.2 to 9.2 dB. While the measured voltage-length product meets the goals of the program, the extinction ratio is less than our goal. Improvements in processing in the next Quarter are expected to improve the ER to the 18 to 20 dB range over large areas.

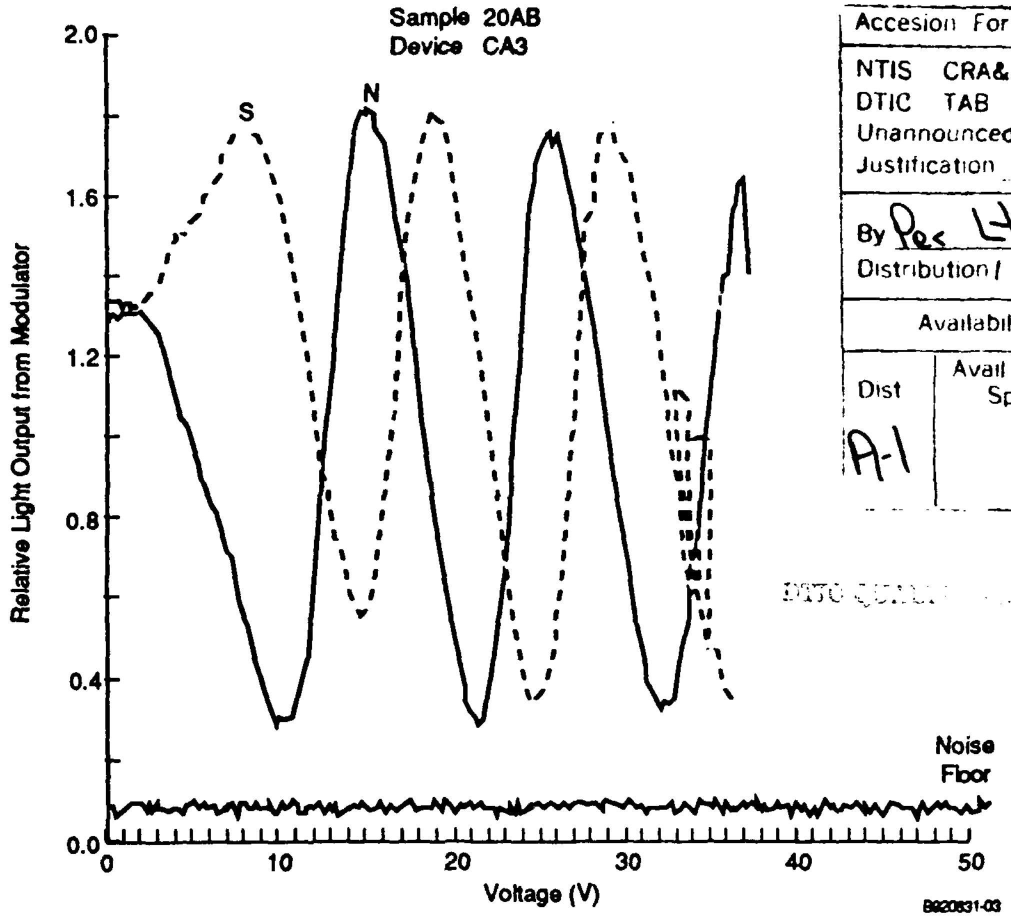

Figure 1. Light output versus applied voltage for the two arms of a Mach-Zehnder interferometer. The plots labelled N and S correspond to reverse bias applied to each of the arms of the Mach-Zehnder independently.

The following specific issues were identified which require further attention:

a. The Cl-based plasma etch process for waveguide circuit delineation needs better run-to-run reproducibility, greater tolerance to process and mask layout variations, and smoother etched surfaces.

b. The insertion loss of our integrated waveguide splitters needs to be reduced by modifying the splitter design to better suit the deep-etch fabrication process. The modal attenuation needs to be

reduced by refining the waveguide layer design and fine-tuning the techniques for growing the layers to better suit our new low-pressure MOCVD growth reactor, and by reducing the channel sidewall roughness by improving the waveguide etch process.

c. It may be necessary to improve our present etched surface passivation for increased breakdown voltage and reduced leakage current, and to establish techniques to anneal out plasma-induced damage that may be responsible for residual photoconductivity currents at high reverse bias voltages. Higher purity waveguide layers may also decrease these leakage and photocurrents.

d. Local variations in the optimum bias voltage required in each arm of the Mach-Zehnder interferometer will complicate dc biasing for low-voltage push-pull operation. In the worst case, customized biasing may be needed for each arm.

Numerous iterations in epilayer growth and in waveguide etching were carried out to refine our procedures for growing low attenuation waveguides using our new low-pressure MOCVD reactor and fabricating etched channels by plasma etching. These improved epilayer samples and process techniques are being used in our second pass at fabricating waveguide modulator arrays using our existing five-level mask set. Concentrating our resources on these activities has delayed our plans for waveguide circuit modeling using a BPM tool, design and layout of our second mask set, and experimentation with pin waveguide device structures. However, these tasks will be accomplished in the next Quarter.

Honeywell also visited the Army Research Laboratory (ARL) at Fort Monmouth, New Jersey to discuss the role of ARL in the OETC program. We met with several scientists to discuss characterization of epitaxial AlGaAs materials and the effects of dry etching processes. We defined a number of joint tasks which we believe will result in deeper insight into the effects of materials and processing on waveguide modulator performance. While the tasks are not in the critical path for developing producible devices under OETC, we believe the successful completion of these studies will result in increased reliability and reproducibility of waveguide modulators.

2.2. AlGaAs modulator array packaging. Task leader: Mr. John Lehman

During the current reporting period we have completed numerical simulations to determine the coupling efficiency and alignment tolerance of the single mode polarization maintaining fiber-to-waveguide interface, commenced on the interface design between the waveguide modulator chip and MAC II connector, and finished a first pass fabrication of the opto-package platform used for the alignment and fixing of the D-fiber to the AlGaAs waveguides.

Numerical simulations of the coupling performance between elliptical core, polarization maintaining, single mode fiber and AlGaAs waveguides have been completed. The simulations were done by calculating the overlap integral of the mode field profiles of the fiber and the waveguide. The simulated mode mismatch loss, using the current waveguide design parameters and D-fiber mode field profile, is 0.7 dB. 1 dB tolerance misalignments could be extracted from the simulation and were found to be ±0.47 μm in the transverse direction and ±0.55 μm in the lateral direction. The longitudinal tolerance (1 dB) was found to be +3.85 μm with a periodic ($\lambda/2$) 0.77 dB difference in the min/max due to the Fabry-Perot effect. Measurements of the coupling efficiency and 1 dB displacement tolerances have been made using an unoptimized AlGaAs waveguide. The lateral, transverse and longitudinal tolerances were ±0.48 μm, ±0.31 μm and +2.45 μm respectively. The coupling loss due to mode mismatch was 1.02 dB. This experimental result was arrived at by numerically factoring out both the Fresnel loss at two AlGaAs/air interfaces and the measured waveguide attenuation.

A baseline approach has been identified for providing the mechanical support for the single mode coupling into the AlGaAs waveguides. Alumina will be the platform on which the fiber and waveguide chip will be attached. Alumina was chosen because its coefficient of thermal expansion (CTE = 6.8 ppm/°C) is very closely matched to GaAs (6.7 ppm/°C). The matching of CTEs provides the basis for a package which can function over a wide temperature range while maintaining acceptable optical coupling.

OETC interactions this reporting period included a visit to AT&T Murray Hill to discuss how to implement the mechanical interface between the Honeywell modulator chip and ATT's MAC II fiber array connector. Several design ideas were discussed and during the next reporting one approach will be selected for implementation. Calculations were done to determine the coupling efficiency between the AlGaAs waveguides and the MAC II fiber array. Because there is a large numerical aperture mismatch between the waveguide (≈ 0.4) and the fiber (0.275), optical losses will occur. Possible methods to reduce these losses include the use of tapered or lensed fibers, or the incorporation of a GRIN lens between the AlGaAs waveguide outputs and the MAC II fiber array to transform NAs for greater coupling efficiency.

2.3. Polymer Backplane Development. Task leader: Dr. Julian Bristow

During the reporting period, we have focused our efforts in three main areas. The first is identification of backplane materials which are widely used in the electronics industry, and which will form the basis for our waveguide backplane demonstration. The second area is in the identification of specific polymer systems for board level waveguide fabrication and encapsulation. The third area of activity has been in the design of an experiment and mask for the determination of the connector design features.

Our target waveguide dimensions for the polyimide backplane demonstration are 25 μm height (or greater) and at least 25 μm in width. We further impose the constraint that the waveguides must be integral with standard backplane materials, and also compatible with polymeric waveguides fabricated on boards which will interface to the backplane. During this reporting period, we have identified the baseline backplane material system, which has also enabled us to define an initial range of candidates for the waveguide polymers.

Our baseline material choice is a glass/polyimide laminate system. Materials commonly encountered in avionics systems for both boards and backplanes are glass/epoxy for lower temperature applications (up to 100°C), and glass/polyimide for higher temperature operation (up to 250°C continuous operation) at approximately twice the cost. More esoteric materials such as PTFE (Teflon-based) backplanes are generally only used when high frequency electrical signals (100s of MHz) are used, and may be four times as expensive as glass/polyimide, while severely restricting the number of layers which may be incorporated into a multilayer board. A significant advantage of optics is that multi gigahertz signals may be routed using polymer waveguides on the lower cost polyimide/glass substrates. Our baseline material choice is glass/polyimide. We currently plan to demonstrate integration of our polymer waveguides with a standard backplane fabrication process, which will involve incorporation of the optical waveguides in a multilayer stack subjected to 1 – 200 psi pressure and perhaps 250°C temperature.

We have obtained a number of glass/polyimide substrates which have been planarized using commercially available polymers in preparation for fabrication of waveguides on these substrates.

The second area of activity in this reporting period has been the identification of a range of material systems for polymer waveguide fabrication, and the design and implementation of an experiment to allow optimization of waveguide routing components for the selected polymer system. A practical waveguide system must incorporate protection against humidity and potentially hostile chemicals, and must also be planar if the waveguide layers are to be as versatile as existing electrical

interconnect layers. We have identified a range of polymers to form as high a refractive index difference between the core and cladding layers as possible, with a target of 0.2. This will allow routing structures with bend radii of a few millimeters with acceptable optical loss. A number of samples of the polymers have been obtained, and will shortly be used in planarized waveguide components to determine both compatibility with each other and with the glass/polyimide waveguide system.

A mask set has been designed and procured to evaluate routing component loss as a function of waveguide width and bend radius for our ruggedized optical waveguides. Three samples have been processed using the mask with oxidized silicon wafers and preimidized polyimide layers. The loss characteristics will be evaluated in the near future. The features of this single layer mask are shown in Figure 2.

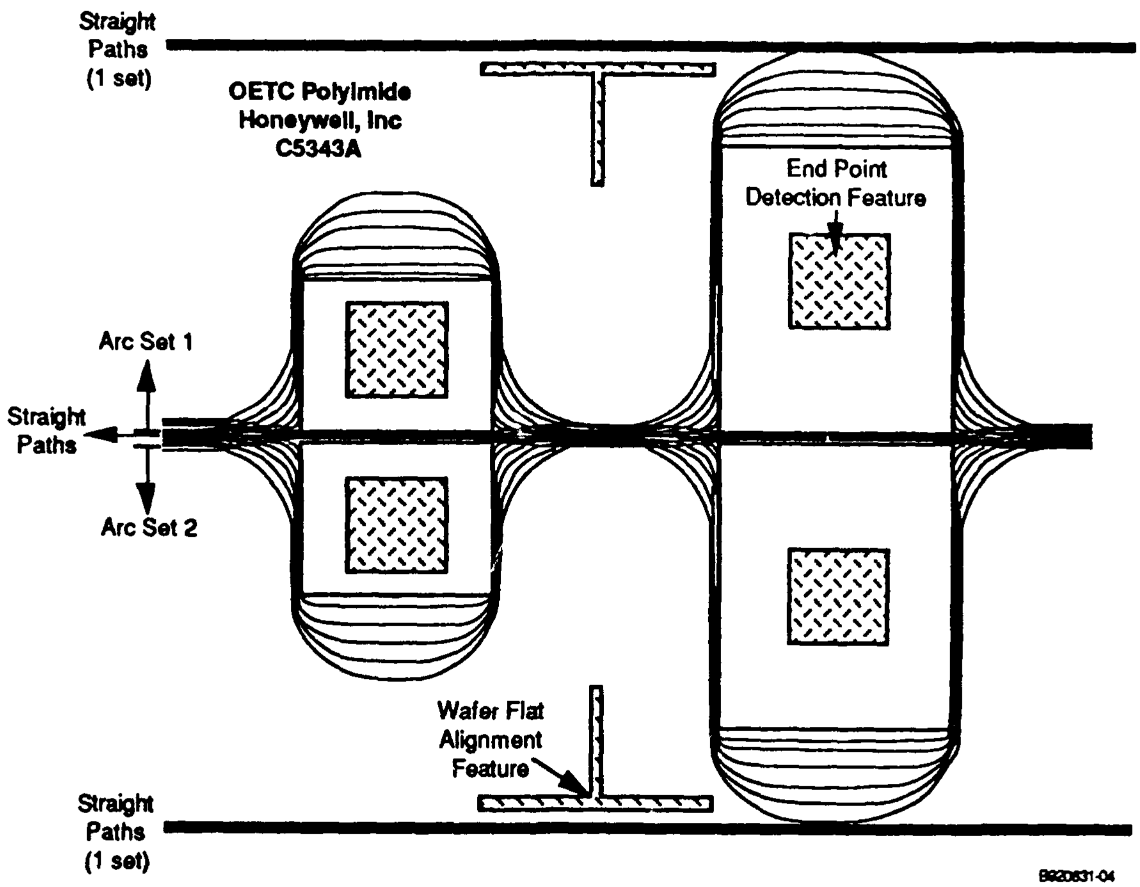

Figure 2. (a) Layout of mask designed to evaluate polyimide routing circuit performance.

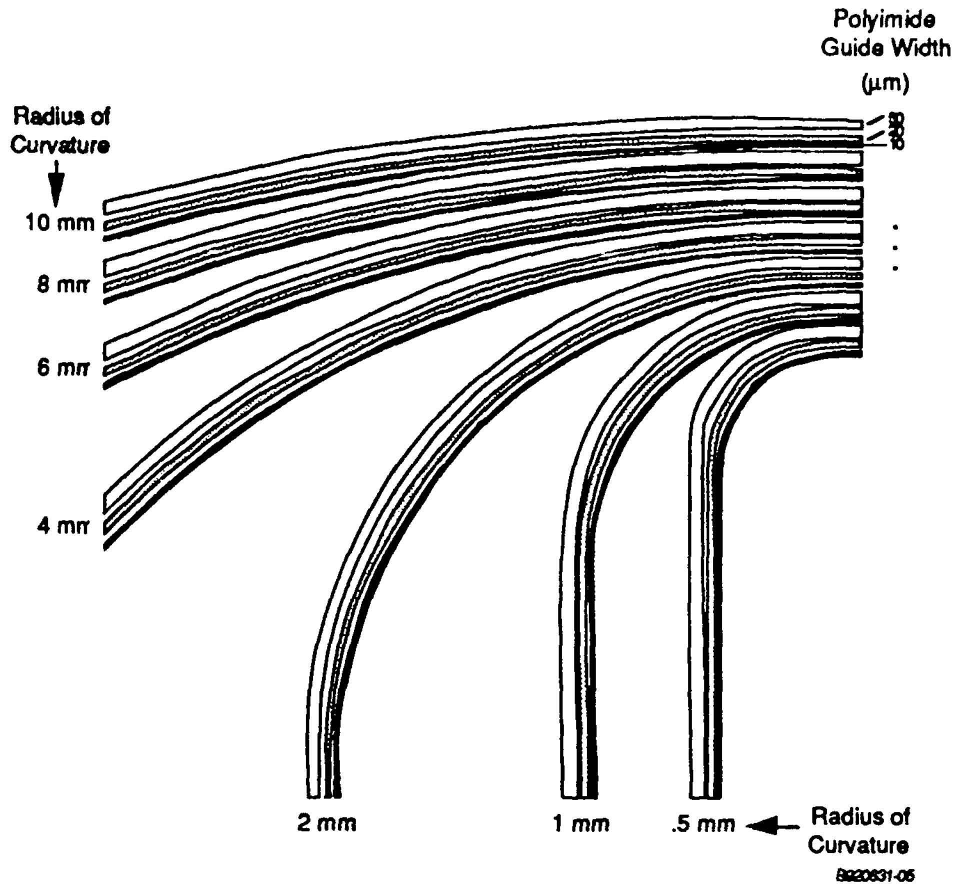

Figure 2. (b) Detail of mask in 2 (a) which shows the variety in radius of curvature and waveguide width to be evaluated.

As described in the last technical report, our baseline approach for interfacing board level waveguides to the optical backplane is to use expanded beam connectors with multiple channels sharing a given connector. Each channel is associated with a particular angle of propagation of the expanded beam with respect to the optical axis. During this reporting period, our third area of development has been the design of an experiment to identify for a range of waveguide geometries and spacings, the maximum attainable waveguide density at the connector for various levels of crosstalk. The experiment will also define the tolerances which must be imposed on a board-to-backplane connector when ultimately implemented in a manufacturable design. A mask set has been designed and is currently being fabricated. Some of the test structures incorporated into the mask for evaluating the effects of lateral and rotational misalignment are shown in Figure 3. Abrupt waveguide bends and splitters are used to illuminate an array of waveguides. Gradient index half-lenses will be mounted on the waveguide array substrate, and a corresponding lens used to image the collimated beam onto a second waveguide array. Unilluminated waveguides will be incorporated with the mask to allow crosstalk evaluation, together with measurements on uniformity of illumination, loss etc. A range of angular and lateral misalignments have been deliberately incorporated to evaluate the effect of inadvertent misplacement in a practical connector. The results of the connector tolerance and performance characterization will be compared against equivalent parameters for directly contacting waveguide connectors to verify the desirability of the expanded beam concept.

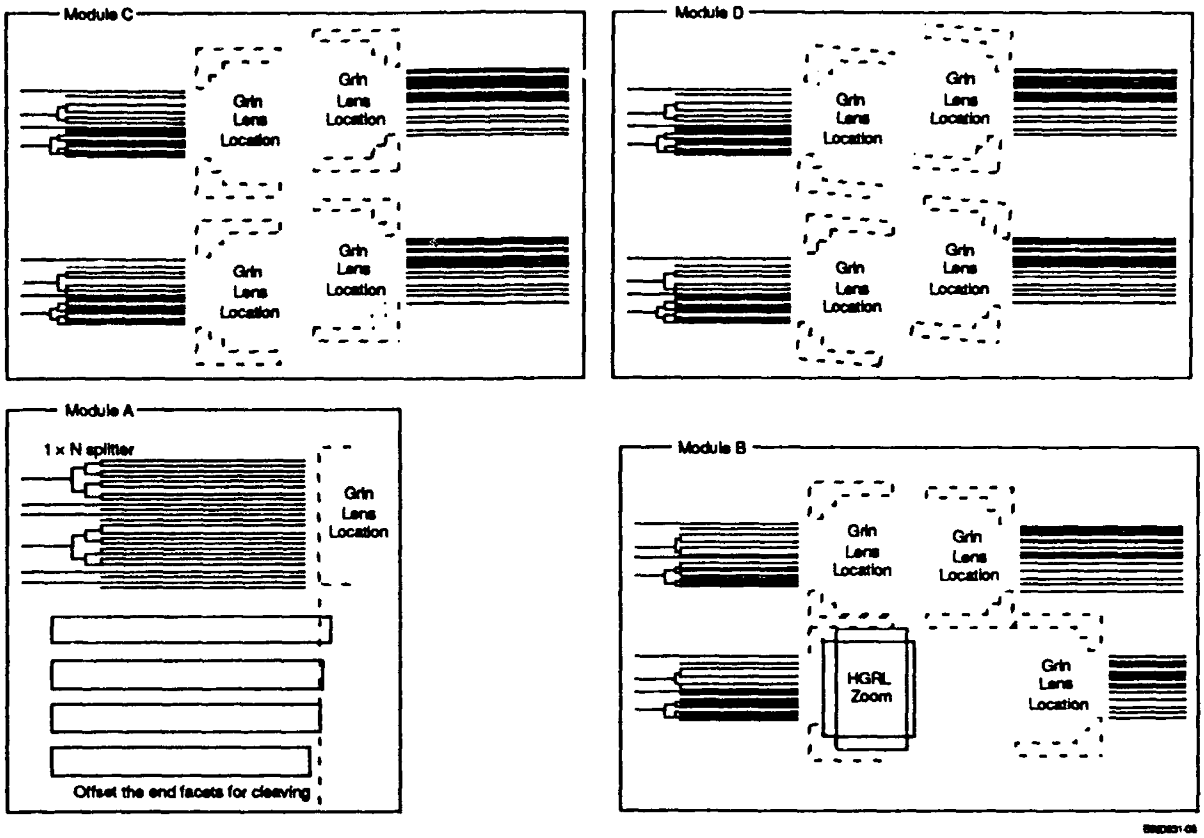

Figure 3. Detail of test structures incorporated on a mask to evaluate the allowed density, crosstalk, and alignment tolerances of the expanded beam connector.

3.0. Third quarter plans

3.1. AlGaAs Modulator Array Development

During the next reporting period we will complete second-pass fabrication and testing of our waveguide modulator arrays using our present experimental mask set with the goal of reaching the optical and electrical performance requirements of unpackaged modulator arrays identified by OETC. We will design, procure and commence processing with a new mask set containing modulator array designs which meet the anticipated packaging and interface constraints, including the fiber pitch on the MAC II connector. This mask will also contain new splitter designs for reduced insertion loss in the 1 × 4 fanout tree and in the Mach-Zehnder interferometers. We will also design, grow, and test pin waveguide modulators to quantify the reduction in voltage-length product and the increase in modal attenuation.

3.2. AlGaAs Modulator Array Packaging

During the next reporting period we will assemble and evaluate the developmental package pieces. Evaluation criteria will include coupling efficiency and how the coupling efficiency changes with externally applied temperature variations. We will broaden our search of materials which are used as adhesives for the fiber and the modulator chip within the package. Promising materials would have low coefficient of thermal expansion, have quick curing times at reasonable temperatures and would operate over a wide temperature range without losing strength. Also the approach for the

waveguide to MAC II connector interface will be finalized and designs for the microfixtures to implement the design will be completed.

3.3. Polymer Backplane Development

During the third quarter we will initiate experiments to planarize glass/polyimide backplane substrates followed by the deposition and patterning of polymer waveguide structures. We will also use the mask illustrated in Figure 2 to begin fabricating routing structures with a number of different core and cladding materials to determine the best combination for planarized and environmentally rugged components. Finally, the mask set illustrated in Figure 3 will be used to fabricate waveguide structures for the expanded beam connector experiments.

4.0. Summary

During the second quarter of this program we have completed the first process run for waveguide modulators and initiated a second process run. The purpose of the first run was to identify the major problems limiting the ability to fabricate devices with good uniformity and reproducibility. The first pass devices met the bias and drive voltage goals of the program, but did not achieve the extinction ratio and loss budget goals. Design and processing issues were identified, and experiments were carried out to optimize dry etching and material growth processes. These optimizations have been incorporated into the second process run. Design improvements will be incorporated into the second mask set, to be laid out during the third quarter. Experiments with the use of p-i-n structures will also be initiated in the third quarter.

An approach to the coupling of single mode, polarization maintaining fiber to the input of the modulator array has been established. Initial experiments of coupling light from fiber to waveguide produced coupling efficiencies close to those theoretically predicted. Piece parts for the optical-mechanical package platform for the input coupling have been fabricated and will be used for a first pass attempt at packaging the input side in the third quarter. We are currently finalizing an approach for coupling the output to the AT&T MAC II connector.

Backplane, polymer waveguide core and polymer waveguide cladding materials for the fabrication of practical, and rugged distribution circuits have been identified and procured. Mask sets have been designed and are being procured to allow the fabrication of polymer board distribution components and the evaluation of the expanded beam connector. Experiments utilizing these mask sets will be carried out in the third quarter.